Development of a Skeletal Model Hand

3. Development of Analogous Interphalangeal Joints

4. Development of Analogous Metacarpophalangeal Joints

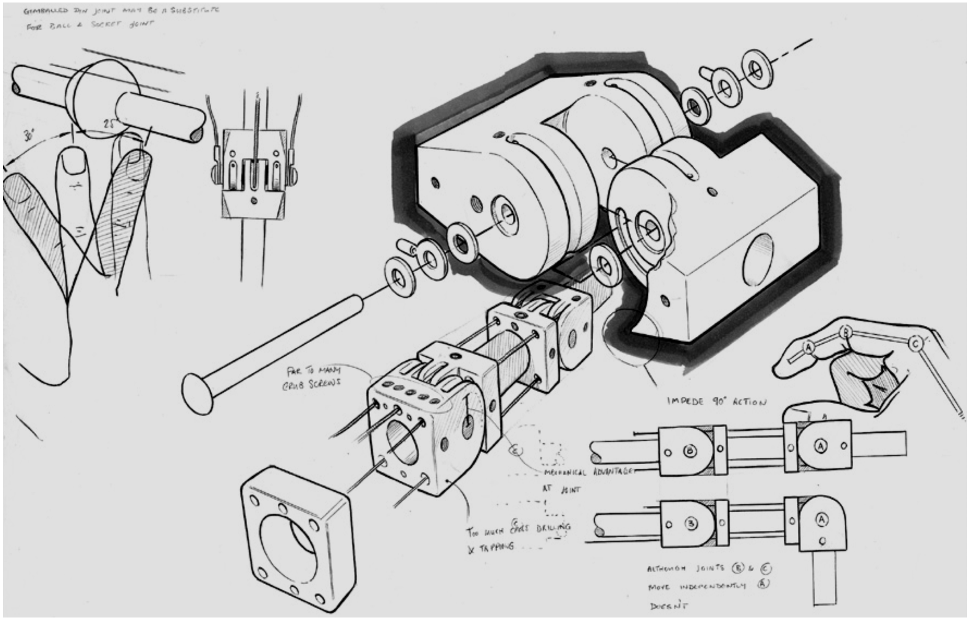
Overview

The work presented in the following two sections represents the first cycle in the development of the articulated model skeletal arm. This first cycle was the development of a prototype skeletal model hand and wrist, and its evaluation.

Although evaluation was initially envisaged to take place at what in the text represents the end of each chapter, it was found experimentally that meaningful evaluation was only possible when significant structures had been developed, such as a whole hand or whole arm. Therefore, the major evaluation of the work described in the first chapters is presented at the end of the second of the two chapters

The following chapters use drawings produced as part of the development of the model hand to explain the decisions made and principles elucidated from the research.

3. Development of Anatomically Analogous Interphalangeal Joints



A Sketch Sheet Used in the Development of the Model IP Joints

The development of the skeletal model hand started with the study of the interphalangeal joints, the last two joints of the finger, as these were considered the simplest joints of the human hand, in terms of articulation.

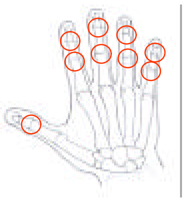
The process identified as creative reasoning, described in the previous chapter, was used to study these joints. Observational drawings were produced from anatomical skeletal models of the human upper-limb to inform sketch book idea development. Additionally, these drawings were complemented by reference to the anatomical literature. The combination of literature review and observational drawing provided both a theoretical understanding of some of the concepts of articulation and a detailed practical understanding of the morphology of the human skeleton.

In the subsequent stage of sketch book idea development ideas were pictorially presented that identified mechanical parallels with the observed skeletal forms. As sketchbook ideas became more refined, a stage of model making was undertaken to test these ideas. The most promising ideas were then prototyped using appropriate techniques to produce joint forms for review. Initial reviewers included amputees and a prosthetics manufacturer.

Literature review indicated goniometric methods for assessing the ranges of movement of the human hand that appeared appropriate to assess the model joints.

The diagram above illustrates one sketch sheet from the sketch book portfolio used in the development of the model joints. Details from sheets such as this, produced as part of the process of creative reasoning are used in the following pages to illustrate the decisions made and the principles elucidated as part in developing the anatomically analogous model IP joint,

This section starts with diagrams explaining some of the anatomical terminology that will be used in the text, and finishes with the challenges that the evaluating the IP joint separately presented.



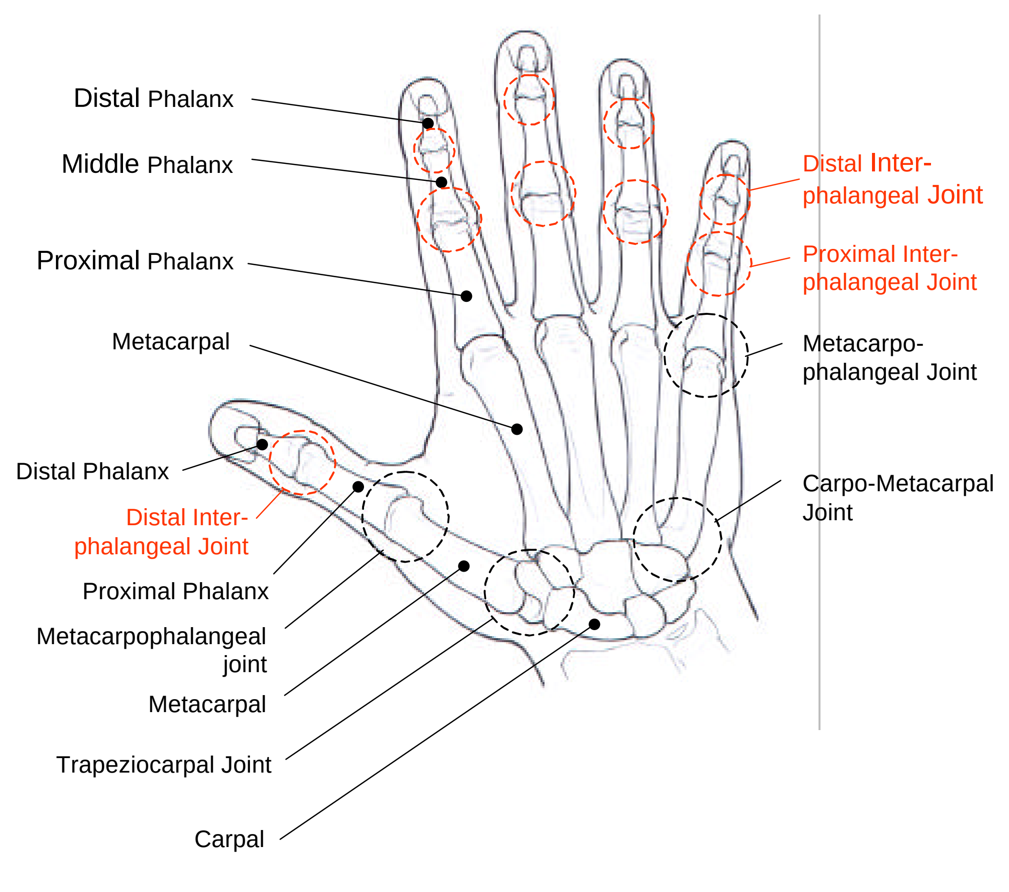


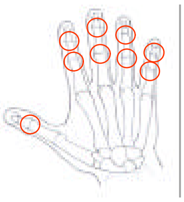
Fig 3.1 The Human Hand - Skeletal Components and Joints

As this section of the thesis describes a skeletal analogy for components of the human hand it is useful for the reader to understand the joints of the human hand.

This figure above shows the outline of a right hand in the palm down or ‘prone’ position. It shows that the skeletal human hand is composed of multiple similarly named joints. The joints pertinent to this chapter, the interphalangeal joints, have been highlighted in red.

A pictogram of this hand will be placed in the top right hand corner of each page within this section to graphically show what joints the discussion within the text is focussing on.

There is more information on this diagram than is discussed in this chapter but the diagram is placed here, at the start of the main body of work, to serve as a reference for discussions throughout this thesis.



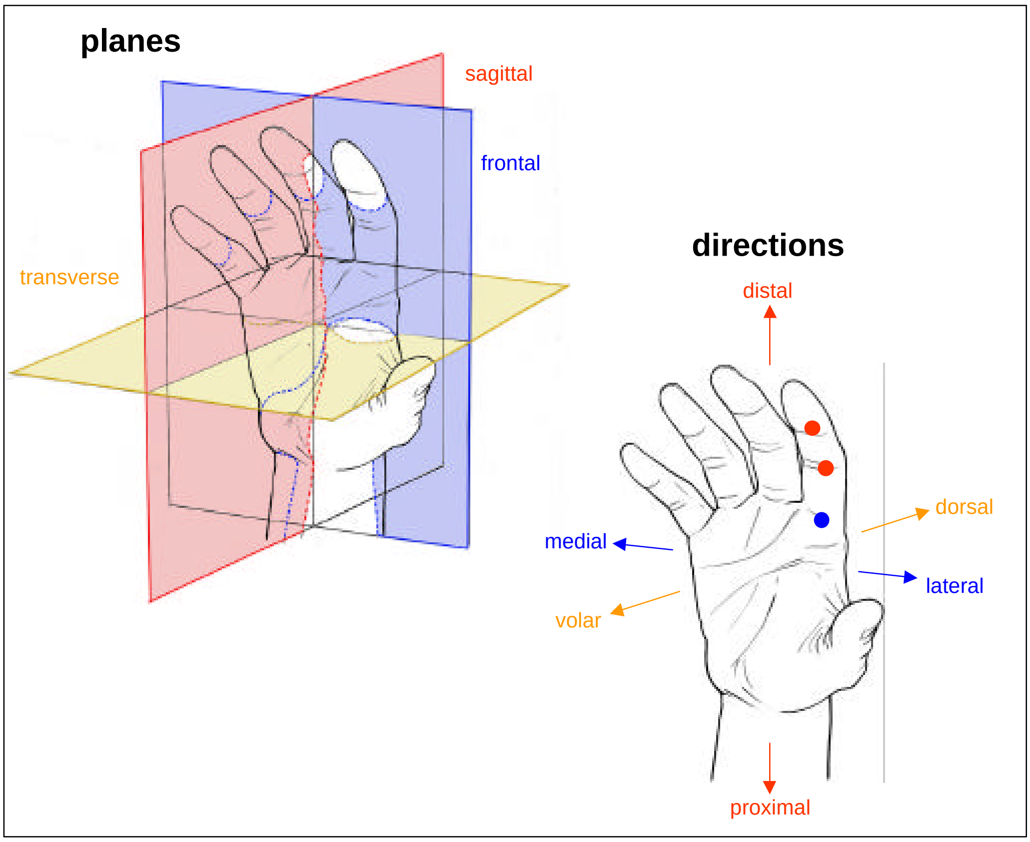
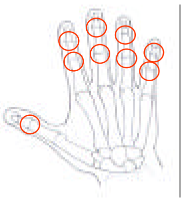


Fig 3.2 The Human Hand Planes and Directions

In addition to being familiar with the skeletal components of the human hand, it is it necessary to be aware of standard terminology used in anatomical descriptions (Kapit and Elson 1993). The diagrams above show how these conventions relate to the hand.

For example, the finger can be described as approximately circular in the transverse plane (Landsmeer 1976) and the metacarpophalangeal joint (blue dot) is proximal to the interphalangeal joints (red dots).



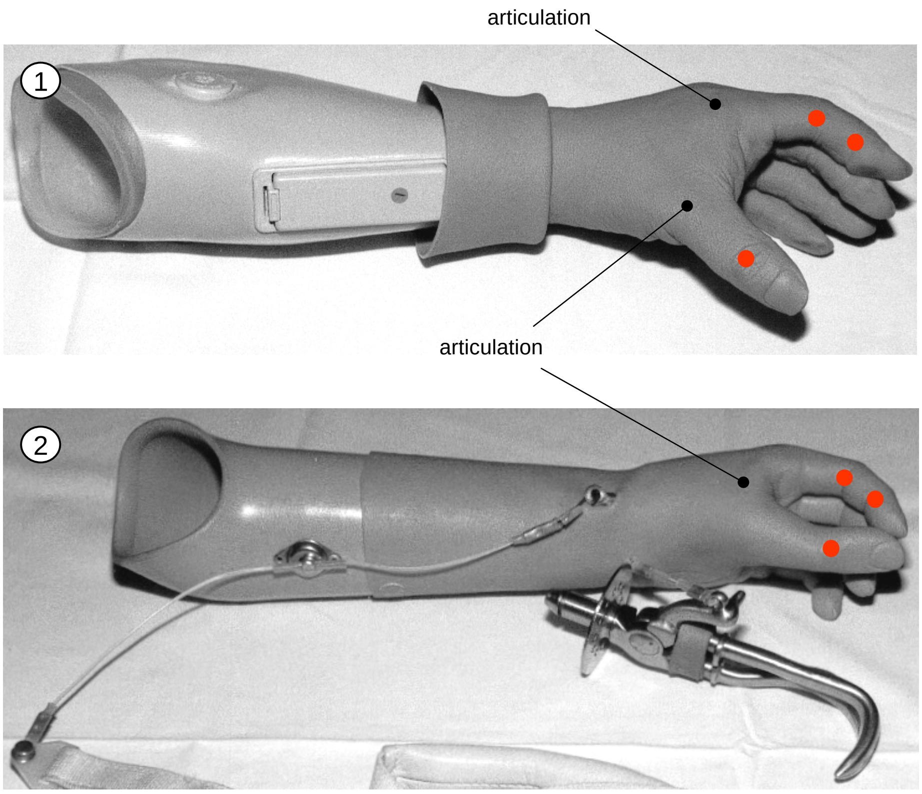
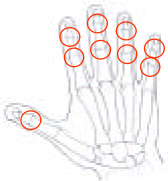


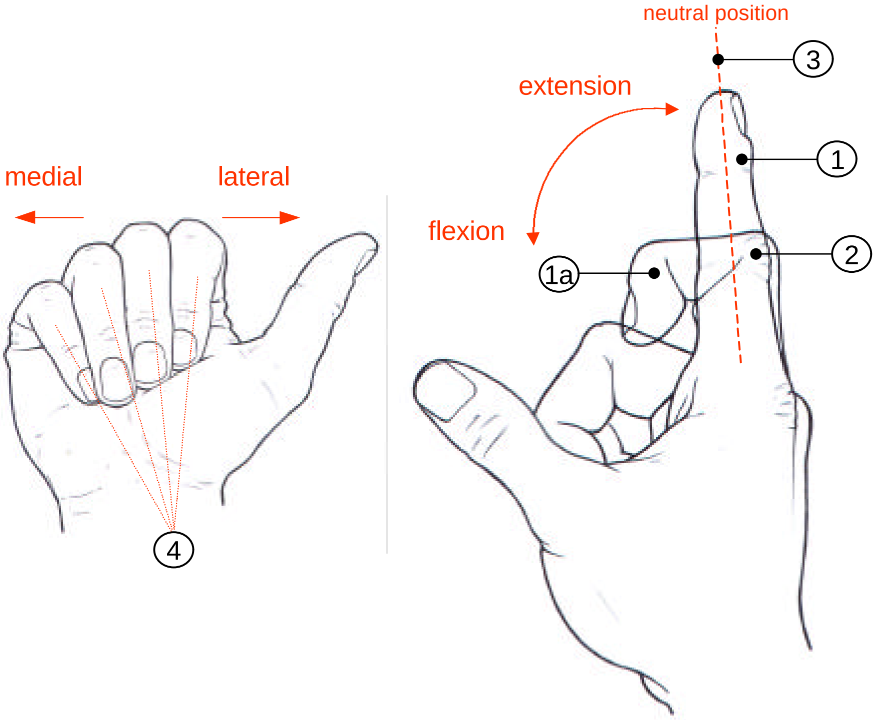
Fig 3.3 Existing Prosthesis Terminal Devices

Although the analogous joints described in the following pages have not been developed incrementally from existing prosthetic archetypes, it is appropriate, as an introduction, to be aware of the form and function of existing prostheses.

The figure above shows a myoelectric (1) and a body-powered prosthesis (2). These devices can currently be prescribed to amputees in the UK. The terminal devices (hand sections) of these prostheses have no articulations at the position of the last two joints of the normal finger, the interphalangeal (IP) joints indicated as red dots (Kapandji 1982). Many reasons have been given for the absence of these joints including limitations of current control strategies to control these extra articulations and the prohibitive cost of the production of extra articulations (Gow 2000). Prohibitive cost has been indicated as a major reason for new ideas and technologies not been manufactured and brought into clinical use, therefore, cost minimisation in any new design is seen as a key criterion (Aghili and Meghdari 1995, Gow et al 1993).

However, from robotics research it can be seen that extra articulations have been added at what may be considered the position of the IP joints to improve the grip functions of robotic terminal devices (Rosheim 1994). Additionally, it has been reported by amputees that there are limitations in the objects that can be grasped when effectively the last two ‘joints’ of the prosthesis are fixed (Rust et al 1997). Personal communication with amputees has indicated that the absence of articulations at these points in the prosthetic terminal device also have an adverse cosmetic effect.





1 Distal Interphalangeal Joint (DIP)
2 Proximal Interphalangeal Joint (PIP)
4 Radial Pulse
1a DIP in flexed position
3 Neutral Position

Fig 3.4 Movements of the Interphalangeal Joints

The process of finding an appropriate mechanical analogy commenced with the investigation of the movements of human IP joints through a literature review.

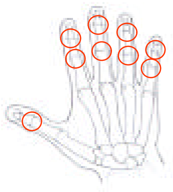
These findings by other researchers may be summarised as follows:

1. The distal interphalangeal joint (DIP) joint has a single degree of rotational freedom permitting flexion and extension of the joint. However, the DIP joint can be passively palpated slightly medially and laterally (Kapandji 1982).

2. The index finger can be flexed in a strictly sagittal plane, however, the IP joint axes of the more medial fingers are slightly oblique so that on flexion they converge at the radial pulse (4). This enables the more medial fingers to oppose the thumb like the index finger (Kapandji 1982).

3. The proximal interphalangeal joints (PIP) have a greater range of movement in flexion than the DIP joints (Daniels and Worthingham 1985), and normally no movement in extension past the neutral position.

4. Like the DIP joints the PIP joints can be palpated slightly medially and laterally. The more medial PIP joints have increasingly oblique axes of rotation, but again can be considered as uniaxial in their articulation (Kapandji 1982).



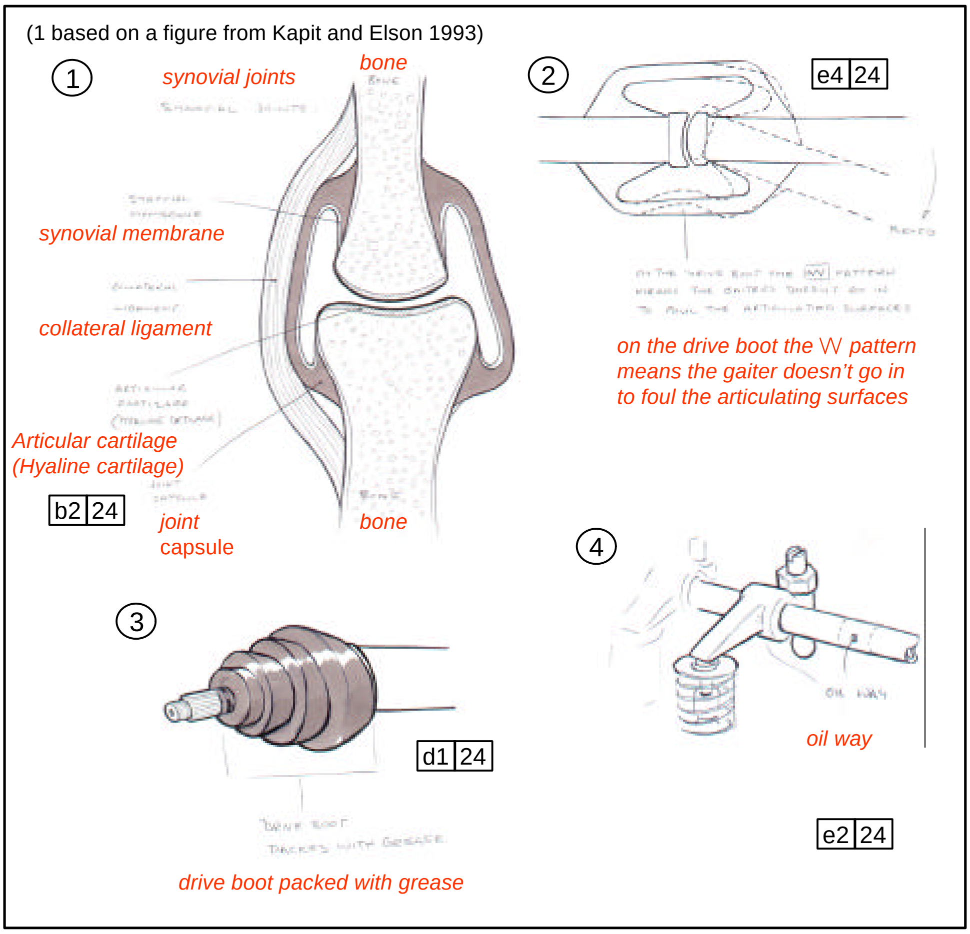


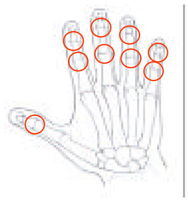
Fig 3.5 Sketchbook Idea Drawings

The literature review additionally indicated that the IP joints (as are the remainder of the joints of the hand) are synovial joints (Kapit and Elson 1993). Synovial joints contain synovial fluid which lubricates the joint, which along with articular cartilage contribute to an almost friction free movement (Kapit, Elson 1993).

Sketch (1) shows the anatomical arrangement of a synovial joint (Kapit and Elson 1993), this sketch was then visually simplified to produce sketch (2). From this simplified sketch possible analogies were considered (3, 4).

Sketch (3), the drive boot of a car, was considered analogous to the joint capsule retaining the synovial fluid. Whereas, sketch (4) likened the articulating segments of the finger running on a film of synovial fluid to a hydrostatic bearing as might be found in an internal combustion engine.

It was evident from this exercise that although analogous aspects could be found in existing engineering components, these were unsuitable for the scale of a model hand so a specially designed solution had to be developed.



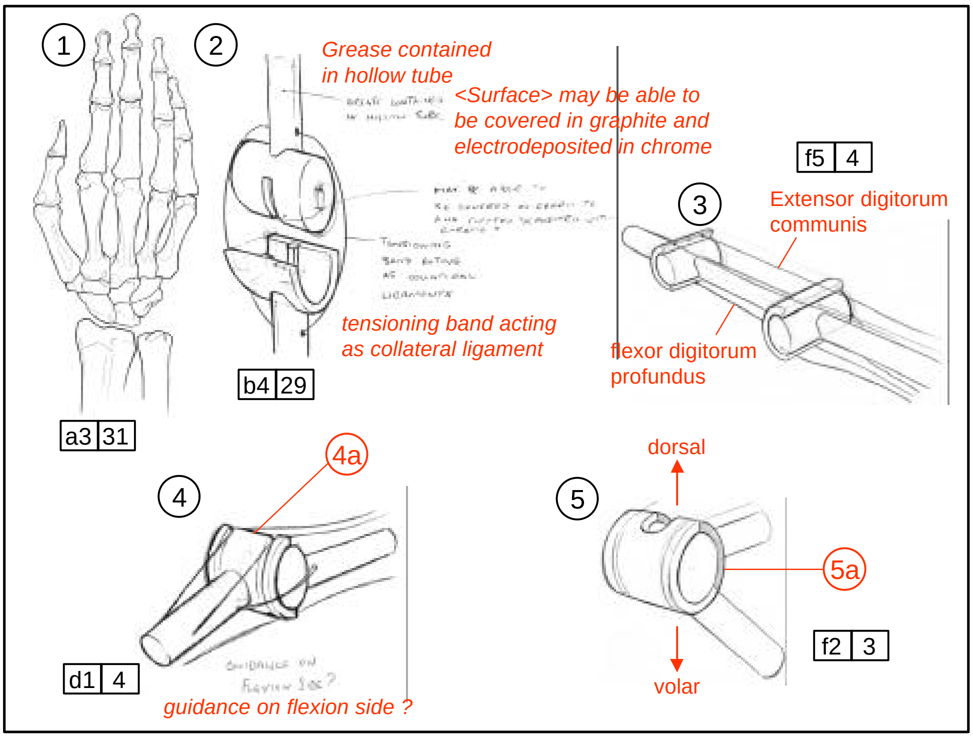


Fig 3.6 Sketchbook Idea Development- Cup and Cylinder Joints

The literature review and initial sketch book ideas investigating potential mechanical analogies were followed by observational drawing studies made from three-dimensional anatomical models (1). This was done to inform the development process of details of the form of the skeletal IP joints.

These observational drawing such as (1) were followed by the production of ideas for an analogous IP joint (2). Sketch (2) shows features similar to the those of the human synovial joint, such as, liquid lubrication and collateral ligaments evident from the literature review combined with a cup and cylinder structure based on observation of the form of the skeletal joints.

The literature review indicated that the fingers of the human hand are activated by tendons. Two of these tendons, the extensor digitorum communis and flexor digitorum profundus run the length of the fingers on their dorsal and volar surfaces respectively (3) (Kapit and Elson 1993).

Sketch (4) was produced to visually test how the joint design would effect an analogous tendon. This exercise highlighted possible problems of wear on a tendon caused by its relative movement over the sharp edges of the dorsal side of the cup (3a).

Sketch (5) explores a potential solution. It shows a hatched section extending around the cylinder to present a constant pulley surface for an analogous extensor tendon to run on (5a). This idea presented the possibility of being able to reproduce the articulation of the finger without the need for collateral ligaments to keep the joint together. This was viewed as a possible means of simplifying the design for manufacture.

Annotations on other sketches performed at this stage included suggestions for possible bearing materials that the joint might manufactured from (e.g. polyamide “Nylon ™”).

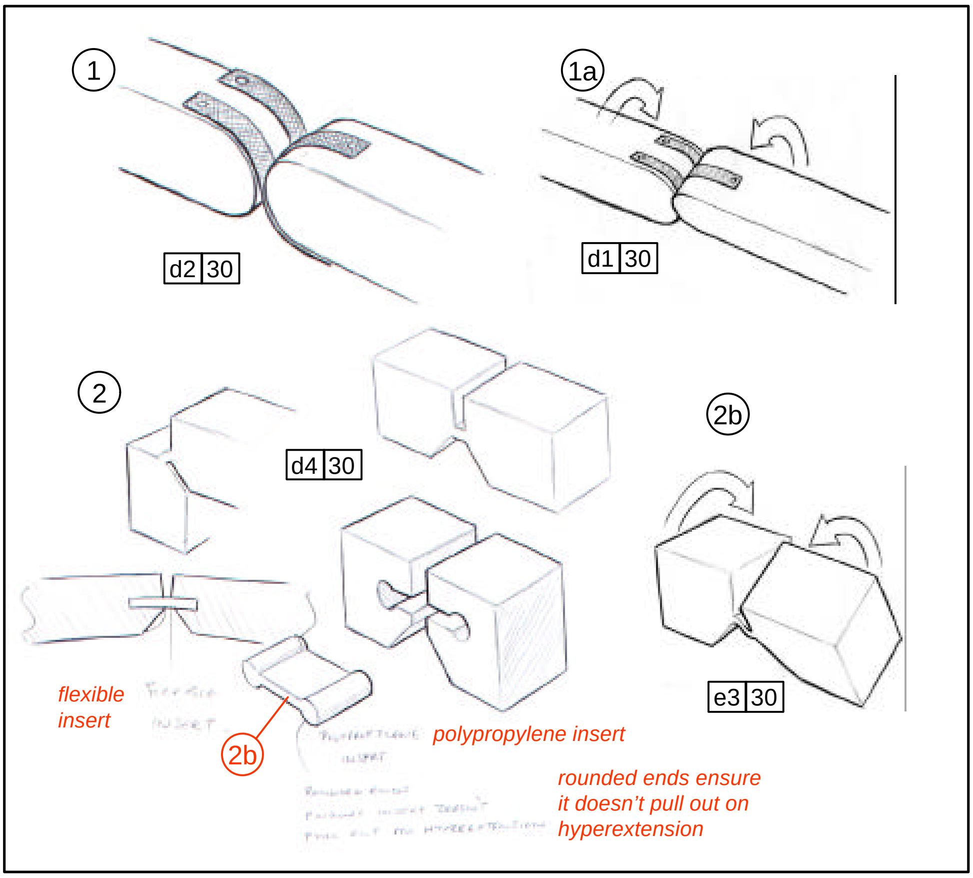


Fig 3.7 Sketchbook IP Joint Ideas - Ligamentous Joints

To test the decision that collateral ligaments would not be needed, it was considered important to explore ideas that used a 'ligamentous' principle (connective soft tissue joining bone to bone) (Kapit and Elson 1993) in their design.

Sketch (1) shows two radiused segments rotating around one another, constrained by crossed 'ligaments' similar to the cruciate ligaments of the human knee (McMinn et al 1993). The idea was rejected as it appeared liable to torsional instability (1a). Also, it has been suggested that, in effect, the IP joint rotates about a single centre (e.g. Kapandji 1982), whereas the rotation produced by this assembly is not about a single centre. This might lead to a cosmetically unacceptable movement in an eventual prosthesis.

Sketch (2) explores a polypropylene hinge shaped to allow flexion and prevent hyperextension. Torsional instability was again foreseen (2b). A solution was considered by increasing the cross section of the polypropylene insert (2a). However, it was thought that this might increase the tendency for the joint to spring back to the neutral position, a property not present in the human synovial joints (Kapit and Elson 93).

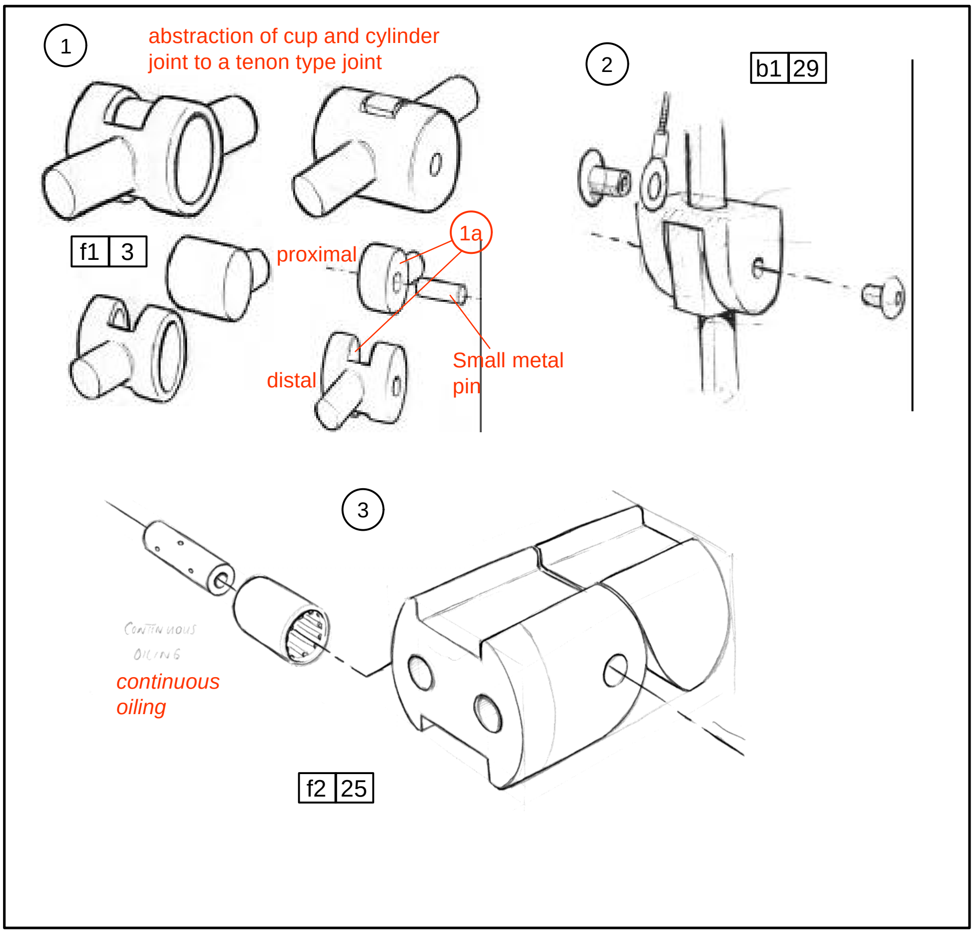


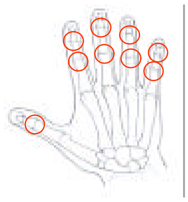
Fig 3.8 Tenon Joint Sketch book Ideas

From the previous exercise it appeared that the cup and cylinder ideas were potentially more successful. Further sketch book idea development resulted in the cup and cylinder arrangement being developed into a tenon type joint (1).

The form of the joint was refined from consideration of the frictional properties of the bearing plastic that the joint might be made from. The articulating surfaces of the cup and cylinder were considered comparatively too large for a freely running plain bearing made from bearing plastic. Consequently, a small metal pin was included in the design to provide both a robust connection between the distal and proximal sides of the joint and, crucially, a smaller area of contact to minimise frictional losses (1, 2).

The interphalangeal joint has no adduction or abduction movements (Kapandji 82), therefore, the lateral and medial sides of the mortise and tenon were considered as thrust bearing faces that would prevent this articulation whilst still allowing flexion and extension (1a).

Alongside the plain bearing ideas, ideas were also developed based on miniature roller bearings (sketch 3) . However, these were rejected on the grounds of excessive weight and problems of durability. It was also considered that such miniature components were too vulnerable to ingress of dirt if used in a future prosthetic hand.



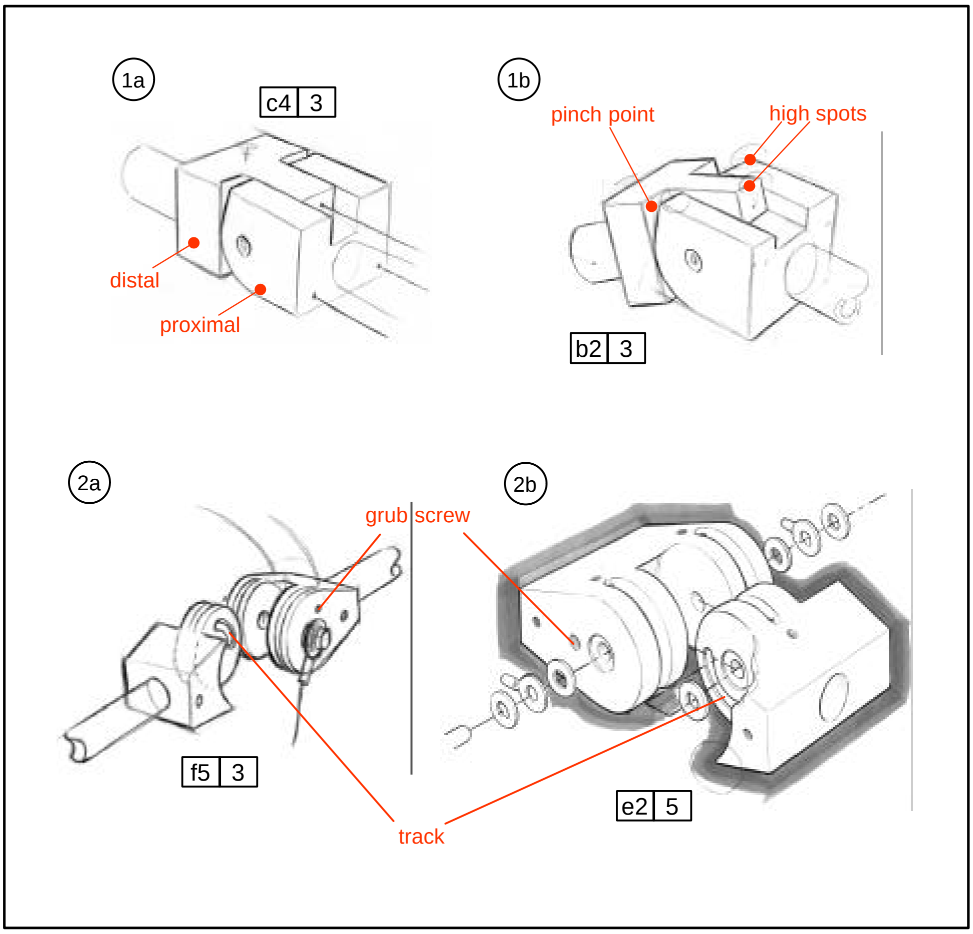


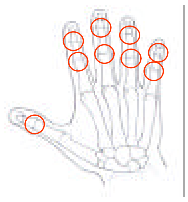
Fig 3.9 Detail Sketches of Tenon Joint Ideas

Refinements to the form of the joint were made through consideration of the range of movement of the joint.

Sketches (1a, 1b) demonstrate how the form of the proposed tenon joint was tested by visually articulating the joint. Sketch (1b) indicated that high spots might protrude from the dorsal side of the joint in the flexed position.

It was speculated that if the joint was to be covered by a thin silicone cosmetic glove, such as those covering the mechanism of the myoelectric devices, these high spots might either tear through the glove on flexion, or could present a 'pinch point' to trap the glove on extension.

Sketches (2a, 2b) show a possible solution using a grub screw running in a track in the interior of the joint, eliminating the necessity for stops on the perimeter of the joint. This was discounted due to the scale of the proposed joint. It was foreseen that without a significant surface area in contact either the grub screw would shear, or, more likely, the softer bearing plastic would deform and then foul the articulation of the joint.



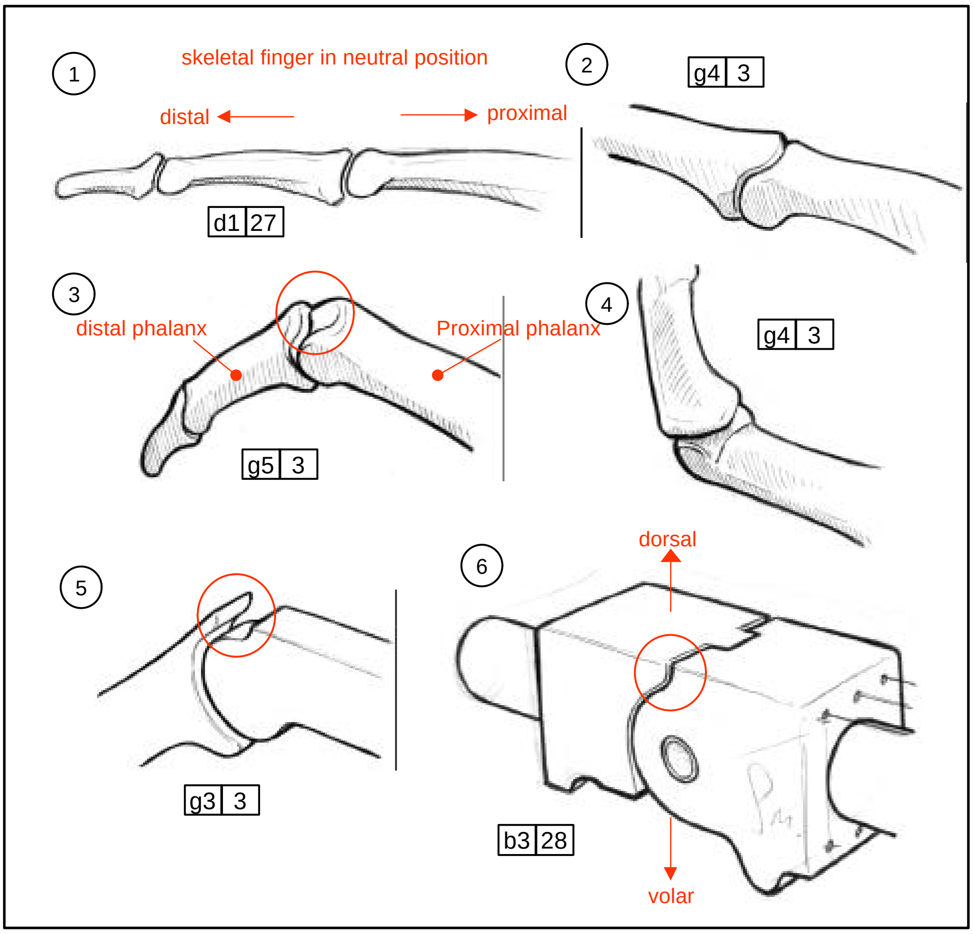


Fig 3.10 IP Sketchbook IP Joint Ideas - Stops and clearances

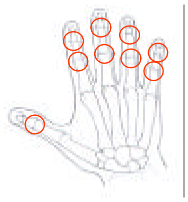
Further observational drawings (1 - 4) were completed to ascertain how the skeletal form of the IP joint contributed to the constraint of the joint.

Initially, studies were made of the joint in the neutral position (1, 2), however, it was found that greater form detail was elucidated when studies were made of the human skeletal joint in partial flexion (3, 4).

The partially flexed studies indicated a dorsal lip on the distal phalanx corresponds to a slight concavity on the proximal phalanx that appears to help the joint resist hyperextension. This stop is formed in such a manner that there are few sharp edges or tight radiuses on the proximal phalanx which effectively remains stationary to the distal phalanx in flexion and extension movements.

Sketch (5), a simplified of the joint form, was made after the observational drawings to visually summarise the findings from the observational drawings.

Sketch (6) shows how this simplified sketch helped in the development of the dorsal stop of the revised joint design.



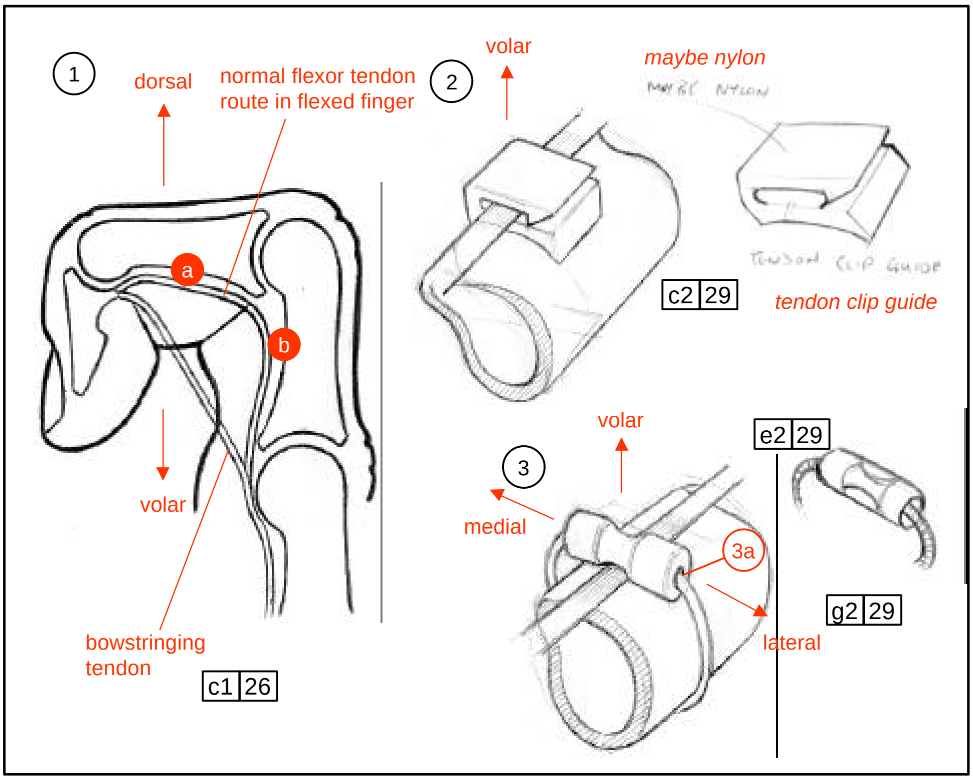


Fig 3.11 Sketchbook IP Joint Ideas - Guides

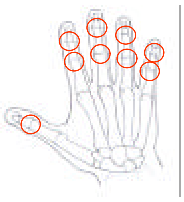
The previous sketches were undertaken to visually explore the effects of flexion and extension on the dorsal side of the joint. Conversely the above sketches were completed to understand effects of flexion of the joint on the volar side, and in particular, the effects on an analogous flexor tendon.

Sketch (1) shows how, without a tendon guidance system, the tendon follows the shortest possible route, an unacceptable effect known as 'bowstringing' (Kaplan 1984).

Like the IP joints the tendons are lubricated through the pulleys by synovial fluid, thus limiting frictional losses (Kaplan 1984). Therefore, the sketch ideas focused on a practical analogy to keep the tendon close to the flexed joint whilst limiting friction.

Initially a moulded Nylon^{TM} (polyamide) clip was considered (2) that could be positioned between the joints at positions (1a) and (1b). This idea was discounted as it was thought that the stresses would be concentrated on the edges of the clip, wearing any tendon material running within it.

Sketch (3) proposed a cylindrical rolling guide, to overcome the problem of sharp edges in contact with the tendon material. This was rejected as it was considered that the problem of friction would be moved to the medial and lateral sides of the cylinder where it would rub against the static band holding it to the finger segment (3a). Additionally, it was speculated that guides positioned at a & b would still allow an unacceptable bowstringing effect.



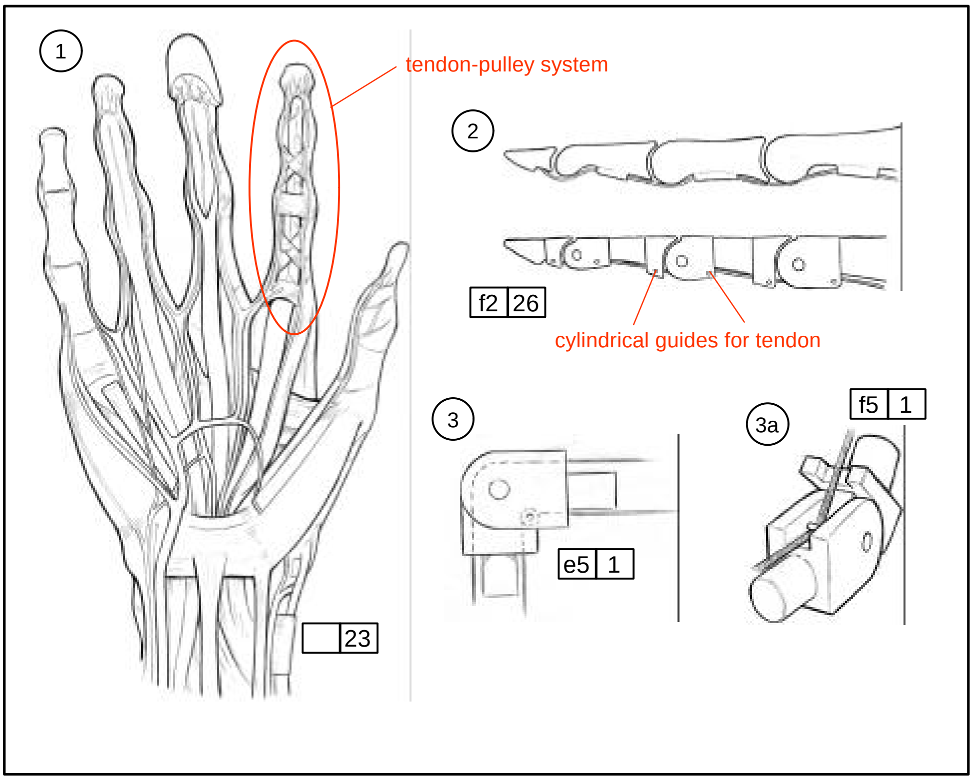


Fig 3.12 Sketchbook IP Joint Ideas - Guides

The inadequacy of the previous sketch ideas indicated that the tendon-pulley system of the human hand might not be fully understood. Consequently, further observational drawing was undertaken from three-dimensional anatomical models to investigate the nature of the soft tissue of the hand and in particular the pulley system of tendons within the finger (1).

This exercise helped to reinforce the location of both the transverse and cruciate pulley bands of the human finger. Importantly, it was observed that the position of the transverse pulley bands are much closer to the centre of the joints than the centre (distal - proximal) of the phalanx. This finding was subsequently checked against against the anatomical literature (Kaplan 1984).

Subsequent joint ideas (2 - 3a) were developed combining the guidance of the tendon with the design of the tenon joint.

Initially, ideas were considered with cylindrical pulleys on both the distal and proximal sides of the joint (2). Through exploring flexion of the joint (3, 3a) it was found that only a single cylindrical pulley was required on the proximal side of the joint. This has the advantage of reducing friction on the tendon which led to the idea of integrating the guidance of the tendon within the joint design.

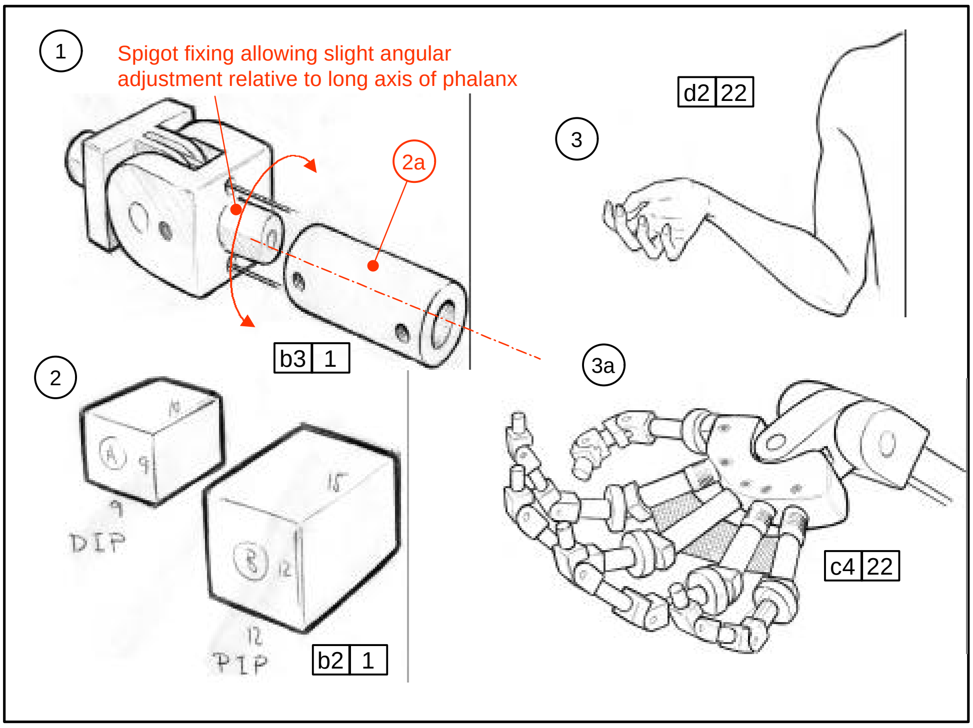


Fig 3.13 Sketchbook IP Joint Ideas - Modularity and Sizing

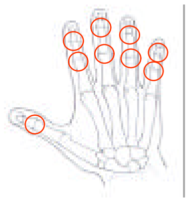
For cosmetic reasons it is considered advantageous if a prosthetic hand matches the size of the contralateral hand of a unilateral amputee (Gow 1993). However, literature review indicates large variations in hand dimensions (Buchholz et al 1992).

Previous sketch book ideas indicated that it was appropriate to combine the guidance of an analogous tendon within the joint design, concentrating the complexity at the joint, leaving the interconnecting sections between joints as simple struts. It was speculated that uniquely scaled hand configurations could be created by changing the length of the simple interconnecting struts, using techniques appropriate for small scale manufacture.

A cylindrical strut was sketched as the interconnecting element between joints. This was proposed to provide the possibility of slight angular adjustment of the IP joints during assembly to allow a finger configuration to flex towards the radial pulse.

It was necessary to relate the prototype to the dimensions of an appropriate human hand. 71.5% of upper limb amputees in the UK are male (NASDAB 1999) and earlier data indicates that this is also true in other parts of the world (Sheridan and Mann 1978). As the research group included a member with 50th percentile male hand dimensions, the dimensions of his IP joints were measured using vernier calipers and the mean dimensions recorded (1). Using joints from fig 3.10, a pictorial hand configuration was sketched (3a).

From this exercise it was concluded that only one IP joint module would be needed. The average dimensions of the PIP and DIP joints were thus taken to develop detailed drawings of an analogous IP joint prior to prototype manufacture.



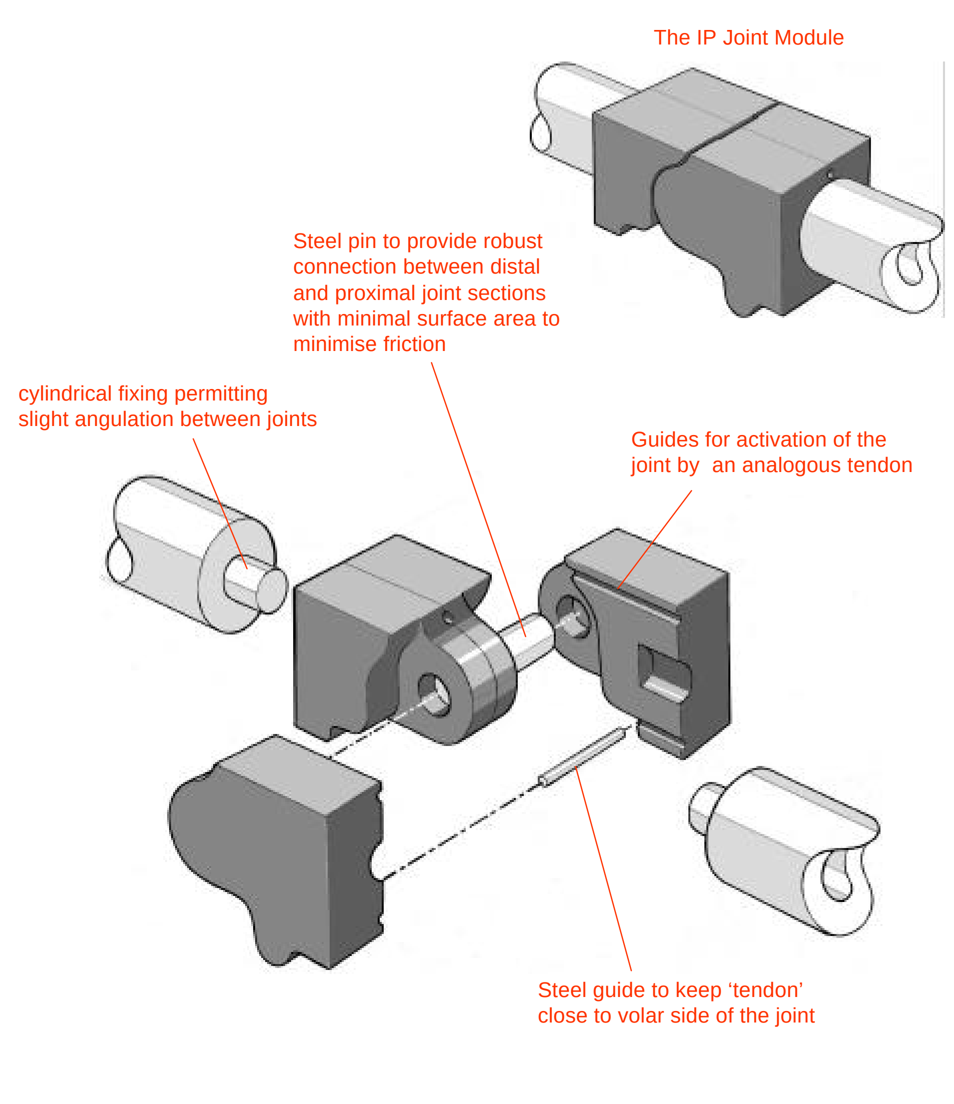


Fig 3.14 Exploded View of the IP Joint

The figure above shows an exploded view of the IP joint design. Design principles embodied in the joint have been labelled.

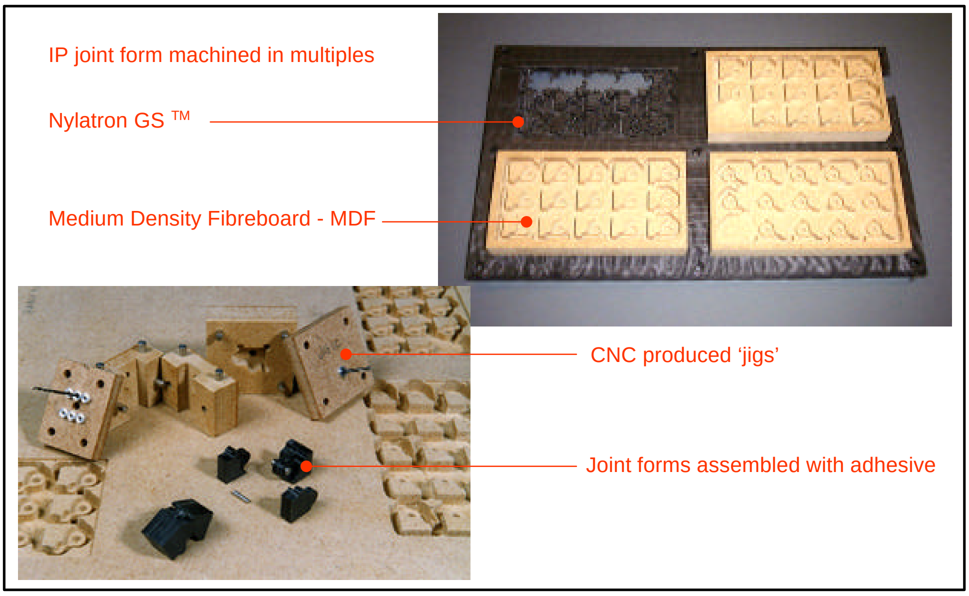


Fig 3.15 IP Joint - Prototype Manufacture

From consideration of the scale and number of joints which must be manufactured to the same design to configure a hand it was considered appropriate to use computer numerical machining techniques (CNC) to create the joint forms.

This process also facilitated revisions of the design to be simply made. In the light of possible revisions the joint forms were initially rapidly machined in medium density fibreboard (MDF) to check that the joint would articulate as proposed in the detailed drawings. Once the forms were confirmed to be correct, multiples of the joint design were machined in a single machining operation out of a lightweight bearing plastic (Nylatron GS TM).

The CNC machined components required further machining on conventional machine tools. This was necessary as the holes required for analogous tendon guidance were outside the plane of CNC machining. To ensure accuracy of the drilling of these holes specially made jigs which were used, again created usng the same CNC processes.

Once machined, the joint forms were assembled using a suitable polyamide adhesive using more jigs to ensure accuracy of alignment.

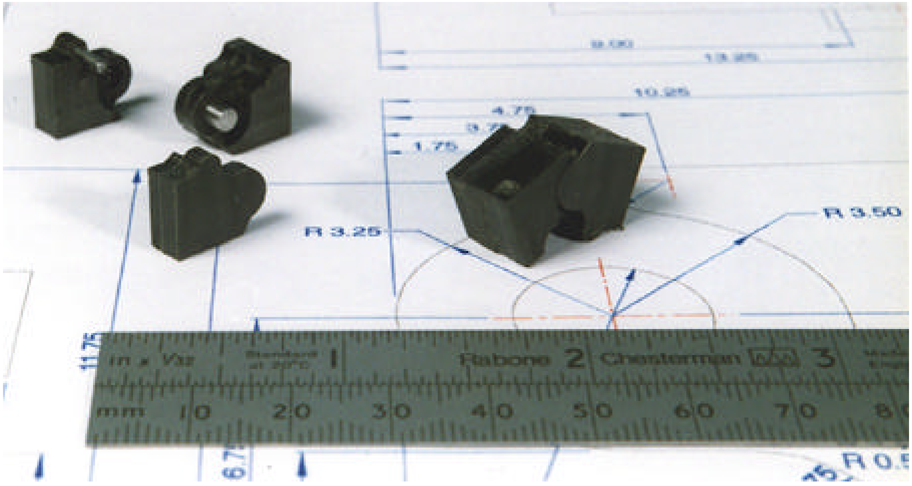


Fig 3.16 The Prototype Analogous IP Joint

The resulting joint appeared to possess a free movement, allowing articulation in a single plane as designed. Additionally, the prototyping methods used appeared appropriate to the production for multiples of these joints necessary for a model hand form.

Due to the anatomically analogous nature of the joints it was thought appropriate for the measurement method used be similar to those used to goniometrically assess the joints of the human hand (Norkin and White 1995). However, using a mechanical goniometer requires that the 'bars' of the goniometer be aligned with the dorsal surface of the finger (Norkin and White 1995). It was considered that these surfaces on the individual model joints were too small using this equipment. Therefore, it was considered appropriate to construct further joints to construct a hand form before assessing the joints goniometrically.

Qualitative Evaluation by Amputees

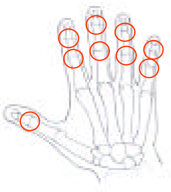
From the start of the research it was considered necessary to attend an amputee support group to understand more of the issues pertinent to the future design of prostheses from their users.   The monthly meeting of the ‘Helping Hands’ Amputee Support Group (based at the Northern General Hospital, Sheffield) was regularly attended. Several meetings had been attended prior to the production of the prototype finger joint and it appeared that the review of the joint by the group might provide significant information effecting its design.

Prior to the presentation of the prototype joint to the group a short introduction was given indicating the aims of the research and the methods being used. The model joints were then presented to the group for their review.

Notes taken at the time indicate that the group was enthusiastic that new research was being undertaken in the prosthetics field. Comments were made that the methods used enabled the members of the group to see tangible evidence research activity, which was thought positive. However, the group indicated that research based on addressing their immediate needs might be more useful. These needs were indicated as modifications to details of their existing devices including various fittings (catches and buckles) were considered ineffective.

There were few comments specifically about the joints other than enquiries regarding the method of their manufacture and the material form which they were made.

The lack of focussed comments towards the design of the finger joint indicated that a more complete model was needed before meaningful qualitative evaluation could be made by ‘end-users’.



Summary

The process of creative reasoning combining observation drawing, sketch book idea development and literature review appears appropriate to eliciting design principles for multiple joints with simple articulations.

The process of observational drawing and sketch book idea develop was found to be iterative. As sketch book ideas developed towards mechanical analogies it was found that detailed aspects of the analogy required the anatomy to be re-observed with closer scrutiny using observational drawing. The development of the dorsal stop on the joint is an example of this iteration (figure 3.10).

The prototyping methods appeared appropriate to the production of multiple precision joints, and presented a means of creating jigs that ensured accuracy in assembly.

In the light of the apparent success of the methods used in the development of the IP joints, similar methods were used to create a mechanical analogies of the other joints of the within the hand (Kapandji 1982). This was done so that a complete hand could be assembled and all the joints evaluated both quantitatively and qualitatively.